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TECHNOLOGY FOR MAGNETOSPHERE PLASMA
IMAGING FROM HIGH EARTH ORBIT.
DESIGN OF A RADIO PLASMA SOUNDER
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Instrument Technology for Magnetosphere Plasma Imaging from High Earth Orbit. Design of a Radio Plasma Sounder

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ABSTRACT

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The use of radio sounding techniques for the study of the ionospheric plasma dates back to G. Briet and M. A. Tuve in 1926. Ground based swept frequency sounders can monitor the electron number density (N_e) as a function of height (the N_e profile). These early instruments evolved into a global network that produced high-resolution displays of echo time delay vs frequency on 35-mm film. These instruments provided the foundation for the success of the International Geophysical Year (1958). The Alouette and International Satellites for Ionospheric Studies (ISIS) programs pioneered the use of space borne, swept frequency sounders to obtain N_e profiles of the topside of the ionosphere, from a position above the electron density maximum. Repeated measurements during the orbit produced an orbital plane contour which routinely provided density measurements to within 10%. The Alouette/ISIS experience also showed that even with a high powered transmitter (compared to the low power sounder possible today) a radio sounder can be compatible with other imaging instruments on the same satellite. Digital technology was used on later spacecraft developed by the Japanese (the EXOS C and D) and the Soviets (Intercosmos 19 and Cosmos 1809). However, a full coherent pulse compression and spectral integrating capability, such as exist today for ground based sounders [Reinisch et al., 1992], has never been put into space.

NASA's 1990 Space Physics Strategy Implementation Study "The NASA Space Physics Program from 1995 to 2010" suggested using radio sounders to study the plasmasphere and the magnetopause and its boundary layers [Green and Fung, 1993]. Both the magnetopause and plasmasphere, as well as the cusp and boundary layers, can be observed by a radio sounder in a high-inclination polar orbit with an apogee greater than $6R_e$ [Reiff et al., 1994; Calvert et al., 1995]. Magnetospheric radio sounding from space will provide remote density measurements of unprecedented precision and coverage in the plasmasphere, inner magnetosphere and magnetopause, from which the structure, inter-relationship, and variations of different plasma regions can be determined [Armstrong Johnson, 1995]. A space-borne Radio Plasma Imager (RPI) could provide a unique global view of the magnetosphere revealing the underlying structure of remote plasma regions, thereby providing a framework for the interpretation of images obtained by other techniques as identified in the technical areas TA1 to TA4 in the MSFC NRA8-8.

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1.0 INTRODUCTION

International advisory groups have identified global imaging of the Earth's magnetosphere as one of the most important and exciting space physics initiatives for the 1995-2015 time period, *i.e.*, the post-ISTP era [Armstrong Johnson, 1995]. Such imaging is essential for gaining an understanding of the global structure and dynamics of the magnetosphere as well as investigating the inter-relationships among key magnetospheric plasma regimes observed previously only by *in situ* measurements. This knowledge of the terrestrial magnetosphere would not only allow us to ascertain an eventual understanding of the solar-terrestrial environment, it is also of fundamental importance to a proper interpretation of plasma dynamical processes similarly operative in cosmic magnetoplasmas too distant for cost-effective explorations.

A bold new idea has recently been suggested by several scientists [Green *et al.*, 1993, 1994; Green and Fung, 1993; Reiff *et al.*, 1994] for performing magnetospheric imaging. Namely, that the well-proven technique of ionospheric radio sounding, practiced over the last three decades [see Jackson, 1986], should be equally applicable to probing the magnetosphere. Preliminary studies have indicated that magnetospheric sounding would be feasible if modern digital designs such as those implemented in the current generation of ground-based ionospheric sounders could be adapted for space flight [Calvert *et al.* 1995]. A magnetospheric radio sounder, the Radio Plasma Imager (RPI) instrument, has been proposed for flight on a mid-size Explorer satellite (MIDEX).

When developed and deployed, a RPI operating between 3 kHz to 3 MHz will be able to map out the large scale, three-dimensional configuration of the magnetosphere. By sweeping the sounding wave frequency from low to high in the two distinct wave polarizations, density profiles of remote magnetospheric plasma regimes can be determined. With the short time delays (within seconds) of the echoes, the radio sounding measurements will monitor in real time the dynamical evolution of the global magnetosphere. In addition, the coherence of the returned signals will also provide information on the roughness of the reflecting surfaces.

The purpose of this project was to define the supporting techniques and technologies necessary for imaging the Earth's magnetosphere from space using radio sounding. We built on our experience with state-of-the-art ground based sounders, coupled with our knowledge of topside sounding and magnetospheric propagation modeling. In spite of the impressive capabilities of modern ground based sounders, it was necessary to improve on the existing instrumentation and the current technology in order to meet the challenges of magnetospheric radio sounding. These challenges arise because of the large sounding distances involved coupled with spacecraft power limitations and the required low RF frequencies (and long antennas) needed to remotely sound low plasma densities.

2.0 SCIENCE CONTEXT

The principal objective of the planned Radio Plasma Imager (RPI) payload is to dramatically improve our understanding of the instantaneous global shape and evolution of the inner magnetosphere under various geomagnetic conditions and observe the transport mechanisms by which solar wind plasma wave and particle energy couple into the magnetosphere and ionosphere. We believe that through the use of state-of-the-art remote sensing instruments a global synoptic view of these mechanisms is possible for the first time. It has been impossible to infer such an understanding of the magnetosphere from *in situ* instruments.

The concept of magnetosphere imaging using radio frequencies has been under study by the RPI Subgroup of the MI Science Definition Team [Armstrong and Johnson, 1995] for several years. The RPI Subgroup has made a strong case for the importance of radio wave sounding in the magnetosphere [Green et al., 1993]. This measurement technique can uniquely provide information about the geomagnetic state of the magnetosphere, such as the location, motion and structure of various magnetospheric boundaries, while also providing important observations to enhance the physical interpretation of data from the other MI instruments. In this last aspect, it can provide important "ground-truth" measurements for other imaging techniques because of its capability to determine precise electron density values of remote magnetospheric structures.

3.0 RPI MEASUREMENT TECHNIQUES

Sounding of the magnetosphere by radio waves uses the same principles as ionospheric sounding. The electromagnetic ordinary (O) and extraordinary (X) modes [Budden, 1985; Stix, 1992] with distinct phase velocities and polarizations are most suitable for remote sounding of magnetospheric plasmas. A transmitted X or O mode sounder wave propagates freely at or very near the speed of light over large distances in the magnetosphere when the wave frequency is much higher than the local electron plasma frequency (f_p) and gyro frequency (f_g). As the transmitted wave enters a region of increasing density, its phase speed increases while its group speed decreases. Upon encountering their respective plasma cutoff (*i.e.*, when the refractive index becomes zero) the wave energy will be specularly reflected. Thus, the measurements of the time delays and frequencies of the radio echoes by the receiver will produce data records of the echoed signal amplitude as a function of echo delay and frequency, analogous to the ionograms, thereby yielding the plasma parameters of the distant reflection points.

The cutoff frequency for the O mode is the local f_p (kHz),

$$f_p = \frac{1}{2\pi} \sqrt{\frac{e^2 N_e}{\epsilon_0 m}} \quad (1)$$

in which N_e is the electron density (cm^{-3}), ϵ_0 is the permittivity of free space, e (C) is the electronic charge and m (kg) is the electronic mass. For the X mode, the cutoff frequency f_x is given by

$$f_x = \sqrt{f_p^2 + f_g^2 / 4} + f_g / 2 \quad (2)$$

From the O-mode swept-frequency sounder measurements, one can determine the electron plasma density profiles along the ray path to the remote plasma regions. Assuming that the sounder signals at different frequencies travel at the speed of light, echoes reflected at different density levels and returning to the receiver at different time delays, yield the virtual range of the target as a function of frequency, the plasmagram (analogous to an ionogram for ionospheric sounding). The true range can then be calculated from the virtual range. The analysis procedure, known as the "true range" analysis, is straightforward and well developed for analyzing ionospheric sounder data. It is an inversion technique that takes into account the density profile dependence of the refractive index between the sounder and the point of reflection at a given frequency. By starting with signals having the lowest frequencies and shortest time delays, hence the nearest echoes, and extending to signals of higher frequencies and longer delays, one can then recover the plasma profile between the sounder and the remote plasma location [Jackson, 1967, 1969; Huang and Reinisch, 1982]. Ground and space-based radio sounders have used this technique quite successfully for decades in mapping the bottomside and topside of the ionosphere, respectively.

Plasma densities in the magnetosphere range from $0.1\text{--}1\text{ cm}^{-3}$ in the auroral plasma cavity and magnetospheric lobes to $10\text{--}30\text{ cm}^{-3}$ at the magnetopause and $10^2\text{--}10^6\text{ cm}^{-3}$ in the plasmasphere and ionosphere. The wave frequencies for magnetospheric sounding, therefore, range from 3 kHz to 3 MHz. Since the sounder waves travel at very near the speed of light over most of the low density magnetospheric cavity, the echo delays measured by a satellite sounder at a few Earth radii above the plasmapause would be a few tenths of a second (using a propagation speed of c gives a round trip propagation time of $43\text{ ms}/R_E$), very short compared to typical magnetospheric dynamical time scales. Therefore, repeated radio sounder measurements can be used to monitor the dynamical evolution of magnetospheric plasma boundaries.

From a given sounder location, it is also possible to receive echoes from different directions arriving from different parts of a remote plasma region. For example, lower frequency echoes from different points in the magnetopause/boundary layer may appear simultaneously with the higher frequency echoes from the plasmapause/plasmasphere. Thus, the salient features of the global magnetosphere such as plasma density profiles and distances to the magnetopause and plasmapause as well as the density structure of the plasmasphere could be measured from the RPI data. From a sequence of density profiles taken during a single orbit (or partial orbit), it would be possible to produce two-dimensional, cross-sectional images of the plasmasphere on the same time scale as the other MI images (10 to 30 minutes). In fact, this technique has been used in the ionosphere [e.g., Nelms and Lockwood, 1966; Benson, 1985 and references therein]. Information on three-dimensional images can also be constructed by fitting several sounder-observed density profiles in different directions with standard models of the plasmasphere and magnetopause such as Angerami and Thomas, [1964], Gallagher et al., [1988] and Sibeck et al., [1991].

Two new aspects not previously pertinent to ionospheric radio sounding must now be considered. First, there can be no assumption of spherical stratification of the plasma (as is true for ground based ionospheric observations) and echoes may arrive from literally all directions. Therefore, to correctly locate the source of the echo it is necessary to not only measure the range but also accurately determine the echo direction of arrival. Second, since echoes will have traveled great distances, magnetospheric sounding will have low signal strengths. Modern digital data processing techniques will be needed to enhance the signal-to-noise ratio.

The construction of images from multiple echoes requires the determination of echo directions. Direction finding techniques have been extensively used on DE-1, ISEE-3, and other spacecraft [see for example: Calvert, 1985; Fainberg et al., 1985; Huff et al., 1988; Kurth et al., 1975,

Yamamoto et al., 1991] for direction finding of natural emissions. Echo wave polarization and direction of arrival can be determined from the amplitudes and phases of the echo signals received separately on three orthogonal antennas. High signal-to-noise ratios are required to determine the echo directions. For sounding of the plasmasphere, direction-finding measurements should have an accuracy of about one degree.

Unlike ionospheric sounding in which the target plasma is for the most part spherically stratified, the radius of curvature of magnetospheric plasma surfaces are no longer large compared to the typical sounder ranges. In this case, focusing and defocusing of the sounding waves by the curved plasma surfaces may be significant. The effect of a curved reflecting surface is to enhance (or decrease) the echo amplitude by a factor of F ,

$$F = 1/2(1 + r/R) \quad (3)$$

where r is the range and R (positive for a convex surface) is the reflecting surface radius of curvature [see *Davies*, 1990]. The factor F reduces the echo signal strength from the plasmasphere by roughly 10 dB, whereas for the magnetopause, it is increased by a comparable amount [*Calvert* et al., 1995]. Finally, with advanced digital sounding and data processing techniques (described below), the echo signal-to-noise ratio can be much enhanced, allowing space-based magnetospheric radio sounding to become feasible.

4.0 INSTRUMENT DESCRIPTION

4.1 Background

The name Radio Plasma Sounder (RPS) has been given to the prototype system developed under this grant, to keep it separately identifiable from the general concept of Radio Plasma Imaging as proposed for specific MI and MIDEX missions.

The current state-of-the-art ground based digital ionospheric sounders (such as the Digisonde Portable Sounder, [Haines, May 1993; Reinisch, 1995]) used for investigating the bottomside of the ionosphere are much more sophisticated than the highly successful topside sounders used in the Alouette and ISIS satellites some 20 years ago. The four satellites in the ISIS program produced over 50 satellite-years of ionospheric topside sounder data and more than 700 publications. The impressive results from the spacecraft sounder program were achieved with instruments operating in an analog swept-frequency pulsed-sounding mode which measured two echo parameters: time delay as a function of transmitted frequency. The current digital ground based sounders measure seven echo parameters:

1. Signal amplitude
2. Phase
3. Doppler spectrum (which can resolve multiple sources)
4. Wave polarization (to distinguish right or left-hand circular polarization)
5. Direction of arrival
6. Echo time delay
7. Frequency

The precise digitally controlled wave forms used in these ground based sounders enable elaborate pulse compression processing and coherent integration to be performed in the receiver which greatly enhances signal-to-noise ratios (by as much as a factor of 1000, or 30dB). Adaptive operation allows computer controlled dynamic frequency selection (choosing low-interference

frequencies during a sounding sweep) to minimize interference, and the powerful embedded computer system provides image enhancement and data analysis to provide high quality measurement data in real-time. These innovations have led to ionospheric sounders that rival the much larger and more expensive incoherent scatter facilities in ionospheric research.

Our approach was to design an instrument which is capable of making high quality images of plasma structures in the ionosphere, plasmasphere and magnetosphere while using an absolute minimum of weight and power. Limiting the power and weight is a challenge because of the large sounding distances involved, the spacecraft power limitations, the wide frequency range required to probe the large range of plasma densities (10^{-1} to 10^{+6} cm⁻³). First, we summarize the current capabilities of the ground based system which was used as starting point for the RPS development.

4.2 Current Ground based Instrument Capabilities

The Digisonde Portable Sounder (DPS) [Reinisch et al., 1992] is a miniaturized and modernized implementation of the Digisonde 128 and 256 sounders [Bibl and Reinisch, 1978; Reinisch, 1986; Reinisch et al., 1989] which were designed and operated over the past 20 years by the University of Massachusetts Lowell's Center for Atmospheric Research. Many features unique to the techniques of ionospheric sounding were pioneered by the Digisonde 256 and its predecessors. These include the following:

- Full spectrum coherent integration of up to 128 pulse echo profiles (each profile is as large as 256 complex amplitude samples vs. time delay), providing 21 dB of signal/noise (S/N) ratio enhancement.

- Coherent integration of phase shifted complex amplitudes from multiple receive antennas, providing a steerable beam forming receiver array to determine the angle of arrival.

- Multiplexed sampling of multiple receiving antennas, allowing the determination of precise location of echo sources by interferometry.

- On-site real-time determination of ionogram trace profile and electron density profile inversion to provide a parameterized model of the current state of the ionosphere.

- A Dial-up communications task operating in parallel with the system's operating software, allowing a remote user to extract real-time data while the system is operating.

The main innovations in the DPS are:

- The addition of digital pulse compression, which makes the use of low transmitting power feasible (300 W as opposed to 10 kW for the Digisonde 256),

- Simultaneous use of multiple receivers in parallel,

- The use of high level language control software with standard PC-DOS (i.e. IBM/PC) data file formats, thus providing great flexibility in the handling and analysis of output data.

Figure 4.1 shows the existing DPS system. The upper chassis contains the system computer (33 MHz 486 based PC), signal generation, reception and processing hardware with and over 200 Mbytes of data storage capacity. The lower unit contains a 300 W solid state amplifier operating



Figure 4.1 DPS Ionospheric Sounding Systems

over the frequency range from 1 to 45 MHz with a nominal bandwidth of 15 kHz. The two 19" rack mountable chassis are installed in a lightweight fiberglass transport case. Not shown are the transmitter antennas (crossed rhombics, deltas or dipoles for circular polarization) and the receiving antenna array (4 crossed loops with active preamplifiers and electronically switched polarization).

The miniaturization was possible because a small low voltage solid state transmitter is used to transmit a long pulse with an amount of energy equal to a high power short pulse (energy = power x pulse duration). The equivalent time resolution of the short pulse is achieved by intrapulse phase modulation using a programmable phase code. The use of a complementary code [Golay, 1961] pulse compression technique is described in Reinisch et al. [1992]. Due to 12 dB of signal processing gain from pulse compression and 21 dB from spectral integration (Doppler processing), the measurement quality of a 300 W DPS is equivalent to a traditional analog sounder of 300 kW peak pulse power. The pulse compression algorithms rely on the phase coherence of the signal over the length of the transmitted wave form, or over any integration periods. Doppler processing in the DPS is achieved by collecting successive samples of the complex echo amplitude at every range (sampled twice per resolvable range bin) then Fourier analyzing this time domain data at each range in order to produce a Doppler spectrum for each range bin. These processing techniques are crucial for the design of the RPS.

The Doppler interferometer technique of the DPS is routinely used to image ionospheric irregularity structures and their velocities [Reinisch et al., 1995]. The radio imaging technique was validated by comparison with incoherent scatter radar measurements [Scali et al., 1995].

4.3 Required Space-Based Instrument Capabilities.

There are several significant differences between magnetospheric sounding and topside or bottomside ionospheric sounding. Among the major technical issues concerning a satellite-borne magnetospheric radio sounder are the low sounder frequencies (which require very large antennas for efficient transmission), the weight, size, and power requirements that define the payload and the transmitter configuration. Aspects of these issues cannot be effectively modeled since they involve many second-order effects and parasitic parameters of the actual devices.

The most critical issues for a magnetospheric radio sounder are the design of the RF power amplifier for the transmitter and the antenna efficiency (as a function of frequency) for a given antenna configuration, the simplest being a long (1/2 km) dipole. These design constraints are imposed by the scientific requirement to sound the low magnetospheric plasma densities over long distances. A major challenge, then, will be in the reception of an echo signal with sufficient S/N ratio so as to enable the measurement of all the critical parameters listed in Section 4.1. Figure 4.2 shows the power radiated from a 500m long wire dipole antenna (a long structure for space, but electrically very short for frequencies in the VLF radio band). These curves arise from placing a limitation of 3000V at the antenna feed point, or 10Watts of power into the antenna whichever occurs first, as a function of frequency. Note that the power radiated at the low end of the band is on the order of a few milliwatts.

Another issue of concern is the proper measurement and interpretation of large Doppler shifts in the returned signal, which will occur when there is a significant component of the wave path along the satellite velocity vector and in case of large magnetospheric plasma motions in the wave reflection region with components parallel to the wave path. These effects can be simulated empirically with an earth-based system by providing a second RPS with a slightly offset sounding frequency. We have used a modified DPS for this task.



Figure 4.2 Power Radiated by 500m dipole limited to 3000 Volts and 10 Watts

The direction of arrival measurement in the ground based DPS rely on a array of receiving antennas, spaced by up to one wavelength, which are sampled simultaneously to determine the phase difference between antennas. Spacing the antennas by the several kilometers required for the very low frequencies makes this technique infeasible for a satellite. Instead the angle of arrival is computed from the three measured complex amplitudes of the received signal on three orthogonal antennas, a technique not feasible for earth-bound observations because of ground reflections. This requires a spin axis antenna which due to mechanical dynamics, must be limited to a much shorter length than is possible for the spin plane antennas. This length is on the order of 10m, while the spin plane antennas can have up to 500m length.

5.0 INSTRUMENT TECHNOLOGY DEVELOPMENTS

5.1 Instrument Development

To meet the objectives of magnetospheric imaging the following tasks were necessary:

- (1) modify an existing DPS system,
- (2) erect a full scale replica of a 1/2 km dipole antenna,
- (3) develop a transmitter impedance matching network,
- (4) develop experimental techniques to simulate the space-based operating environment (Doppler shift, range closing, and multiple sources) on Earth,
- (5) fabricate a 3 antenna receiver array to provide single point angle-of-arrival measurements
- (6) investigate the effectiveness of various signal processing algorithms, especially stepped-frequency radar, Doppler processing, and pulse compression of various phase code sequences.

5.2 Modifications to the DPS system

Modifications to the DPS were necessary in order for it to generate the lower frequencies (3 kHz to 3 MHz vs. 1 MHz to 40 MHz for the existing DPS). Figure 5.1 shows the overall RPS system while 5.2 shows a more detailed block diagram of the receiver sub-system, 5.3 shows the transmitter sub-system, both of which required selection of a new set of IF (Intermediate Frequencies) and LO (Local Oscillator) frequencies, as shown in the diagrams. Frequencies of 100kHz to 3Mhz were implemented in the prototype, while provision for another operating band of 3kHz to 100kHz has been included in the design (as shown in Figure 5.2). It was possible to achieve the target bandwidth of 250 Hz with magnetically coupled ferrite core inductive circuits, both in the transmitter and receiver design. The use of these circuits, similar to those implemented in the DPS, enable quick recovery from the signal overload caused by the transmitted pulse, such that received echoes can be detected "immediately" (about 5msec) after the transmitter shuts off. A wave form consisting of eight 4msec phase code chips is generated to provide a range resolution of 600km.

5.3 Construction of a 500m long transmitter antenna

Using two 30m towers at our Millstone Hill field site (Figure 5.4), a 500m dipole antenna was constructed with the feed point at ground level and the ends of each dipole supported at ground level, while the middle of each element is supported 30m in the air at a point 30m from the feed point. The wire is a stranded #24 phosphor-bronze, made up of 7 strands of #40 wire. The balanced feed point is connected to the unbalanced feeder cable by an 8:1 step-up wideband balun transformer, made of low-impedance transmission lines wound on a high permeability ferrite core.

RPI Payload Block Diagram

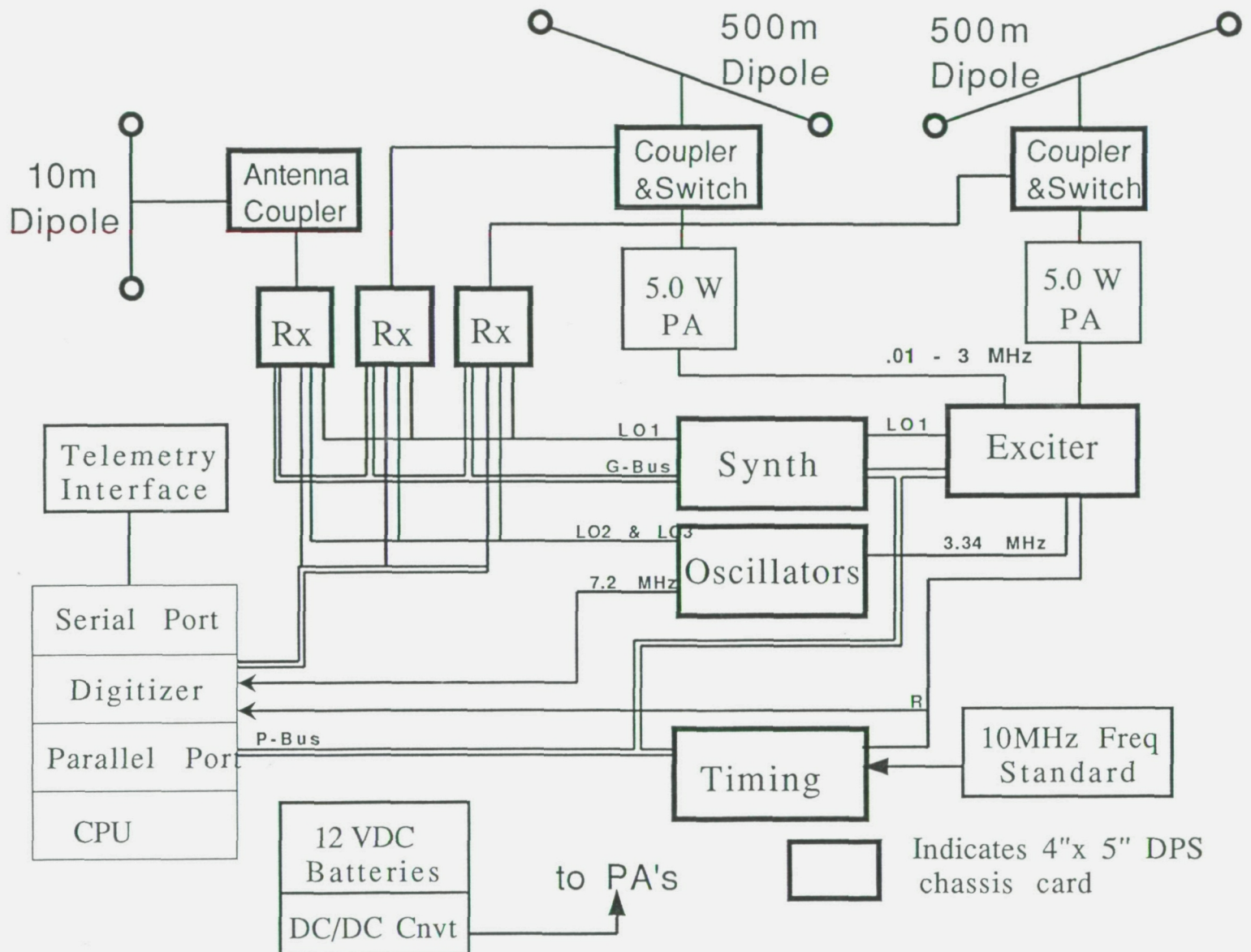


Figure 5.1 Satellite Payload Block Diagram

RPI Receiver Diagram

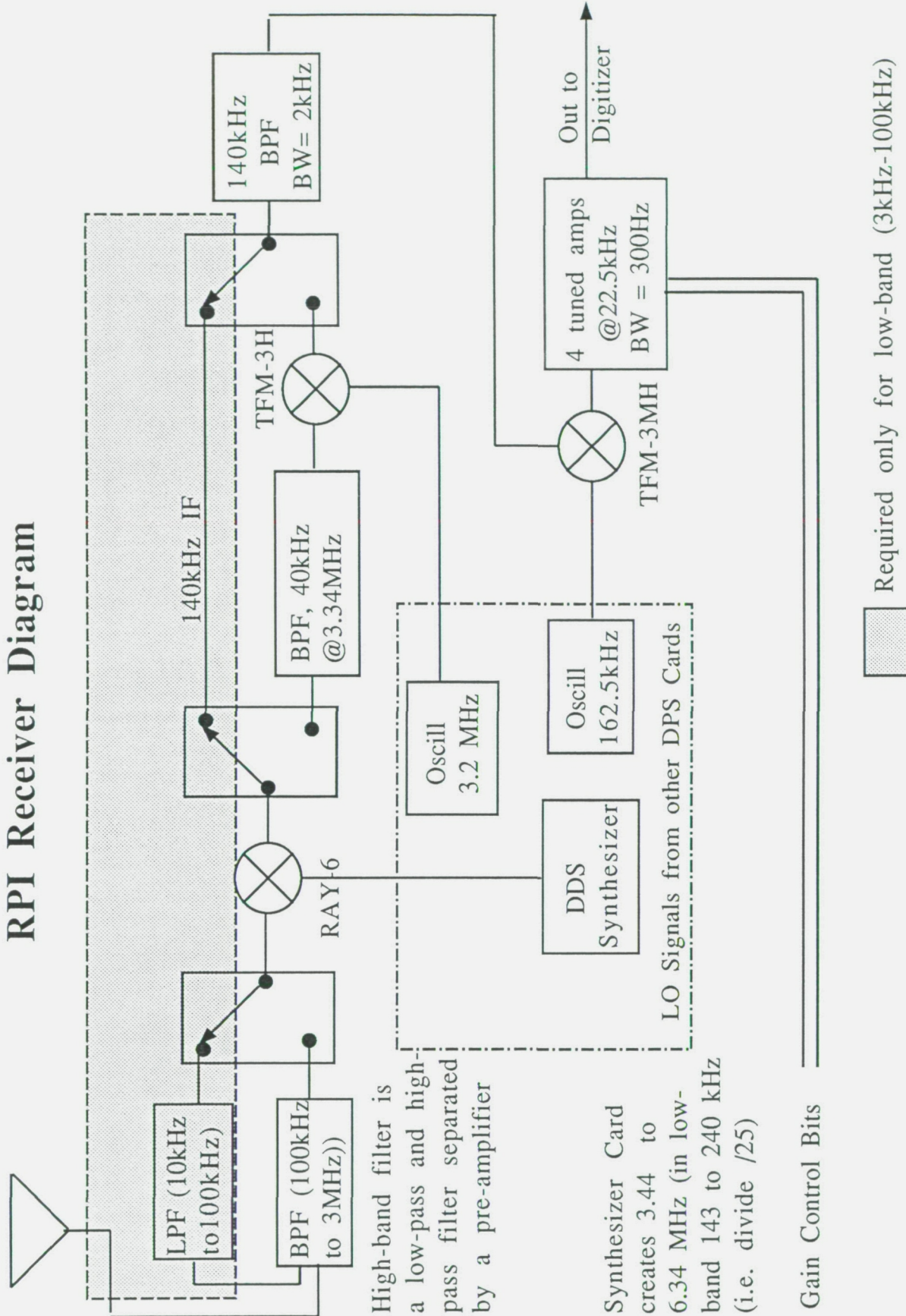


Figure 5.2 RPS Receiver

RPI Transmitter Diagram

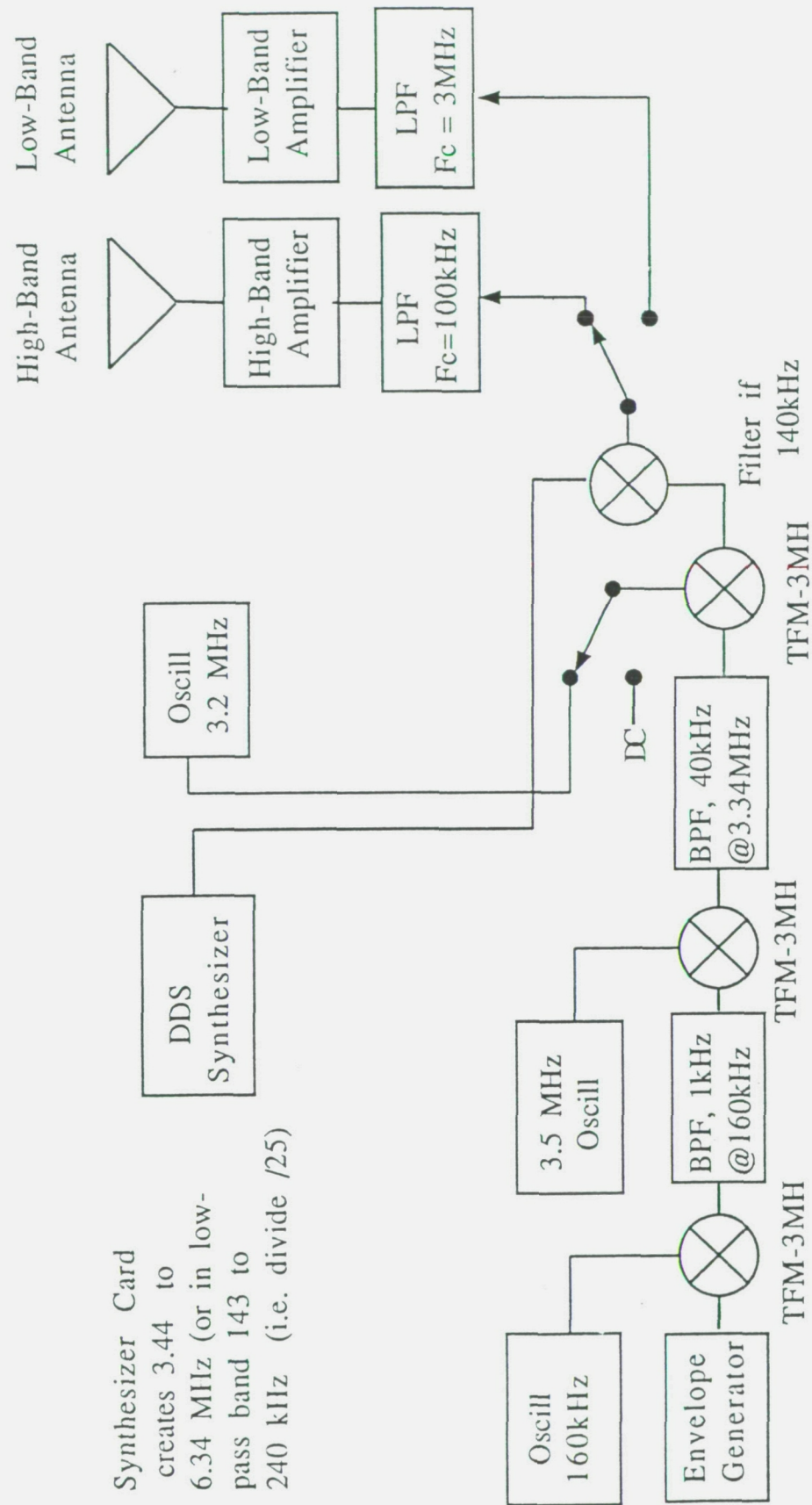


Figure 5.3 RPS Transmitter

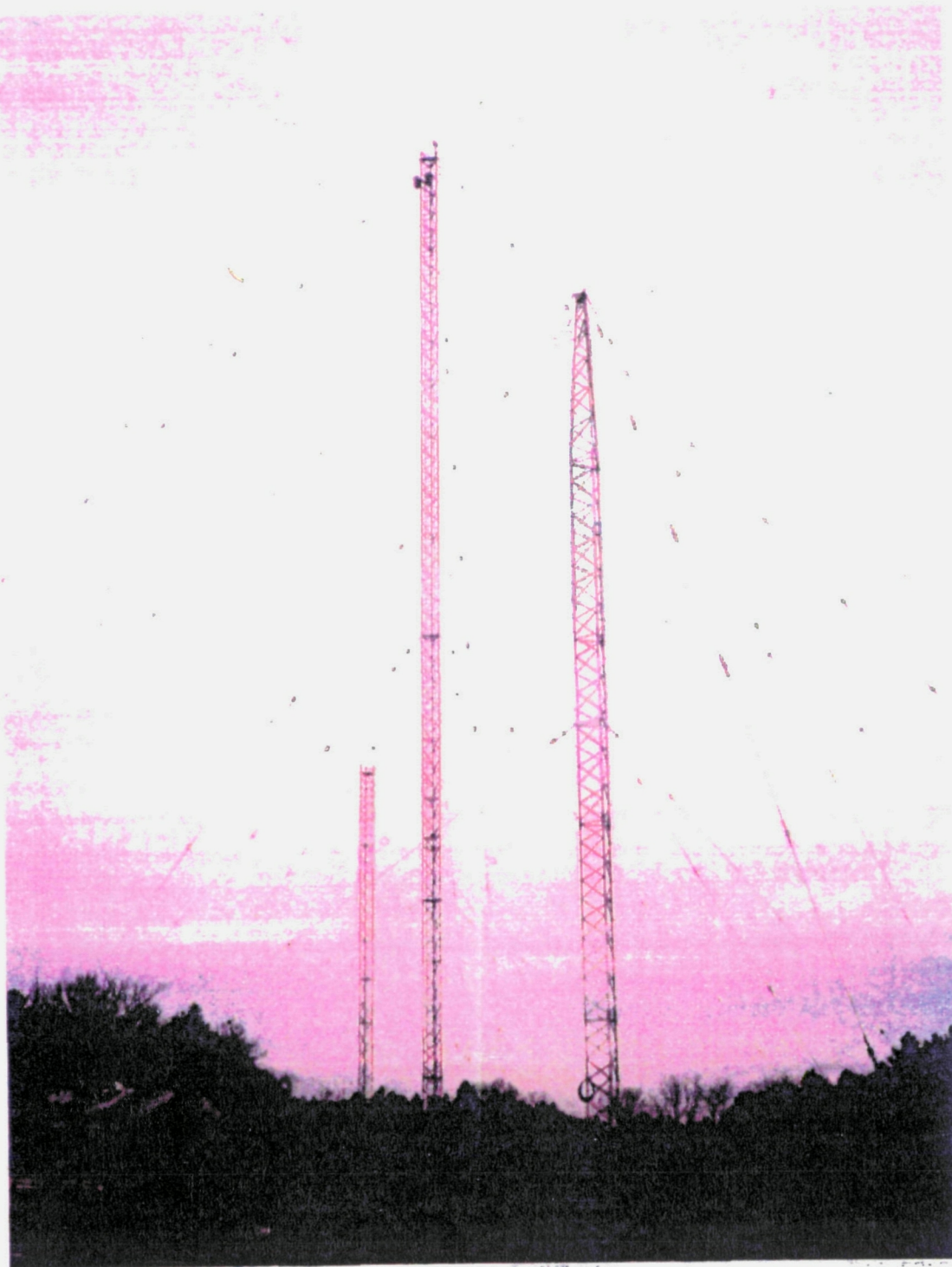


Figure 5.4 RPS Test Site at Millstone Hill

The input-output characteristics of this balun connected to the 500m dipole are shown on Figure 5.5. Since there should be an 8:1 voltage step-up, the input voltage is plotted times 8 to show the conversion loss, which is negligible (about 1dB) all the way from 5kHz to 2MHz.

5.4 Development of RF Power Transmission Techniques

Antennas which radiate RF energy efficiently have physical dimensions on the order of a quarter or half wavelength, up to several hundred wavelengths (e.g. a parabolic reflecting dish antenna), however, as the antenna becomes much smaller than a wavelength, efficient radiation is not easily achieved. For frequencies of 3 to 100kHz the RF wavelength is 100km down to 3km. Therefore, for operation over the low band of the RPS frequency range a reasonable space borne antenna will be extremely short. Both the use of multiple antennas of different lengths or use of the deployment/retraction mechanism to change the antenna length are unacceptable, therefore we decided to attempt to efficiently radiate from a fixed geometry antenna of 500m. This length was selected because antennas of nearly this length have previously been used in space, so this feature of the instrument would not introduce an unknown risk factor.

Figure 5.6 shows a curve of the input impedance of a 500m dipole antenna using 2mm diameter wire. The impedance is as high as 80kohms at the 3kHz end of the band and drops to less than 1kohm at 100kHz. This means that at low frequencies it will take an extremely high voltage to be able to induce a current of sufficient magnitude to radiate even a few milliwatts of power (i.e. 3000 volts). The curve overlaid on the impedance curve is the radiated power, given a constant 3000V RMS at the antenna feed point, until at 125kHz the transmitted power becomes limited to 10Watts by the available transmit power. This limit of 3000V and 10Watts was used for the remainder of the design analysis; however, most results can easily be scaled up or down for a different choice of limiting parameters. Now that limiting parameters of 3000V and 10Watts have been introduced, the next step in the design is to determine the best means of creating the 3000V signal. The options are to create the signal at 3000V or to create it using low-voltage electronics (i.e. <50V) and stepping up the voltage in tuned circuits, and/or transformers.

The most efficient transmitter amplifier is a lossless switch, which simply applies first a positive voltage, then a negative voltage to the antenna, alternating at the RF carrier frequency. This type of transmitter (Class D) is not suitable for amplitude modulated signals such as AM, but is ideal for phase or frequency modulated signals, which the RPS is designed to generate. Figure 5.7 shows the result of applying this type of transmitter to the electrically short (500m) dipole. Since the antenna impedance of 20,000 ohms (at 30kHz) is almost entirely capacitive, the antenna simply charges up to the applied voltage level (which requires much less than a half cycle of applied RF) thus creating current spikes which contain very little energy and would create such a broad transmitted spectrum that very little received energy would pass through the 250Hz bandwidth of the receiver. This simple analysis convinced us that a tuned circuit would be needed if a high efficiency amplifier is used. The other advantage of tuning the antenna is that the amplifier need not operate at a high voltage in order to make a high voltage on the antenna. Figure 5.8 shows that the unit step in voltage at the input to the tuning inductor applied by the lossless switch, is transformed into an undistorted 12A current feeding the 0.5ohm radiation resistance of the antenna at 30kHz. This is quite idealized, in that there is about a 20ohm wire resistance in the antenna in series with the 0.5ohm radiation resistance (EM radiation loss) and realistically a 10 to 50 ohm loss resistance in the resonant circuit, however, these losses are unavoidable and are acceptable.

The alternative to an efficient Class D transmitter is a linear Class A amplifier. This amplifier would always consume over 30Watts of power, even when radiating only a few milliwatts of power. This inefficiency places too much of a power load on the satellite platform and is therefore undesirable.

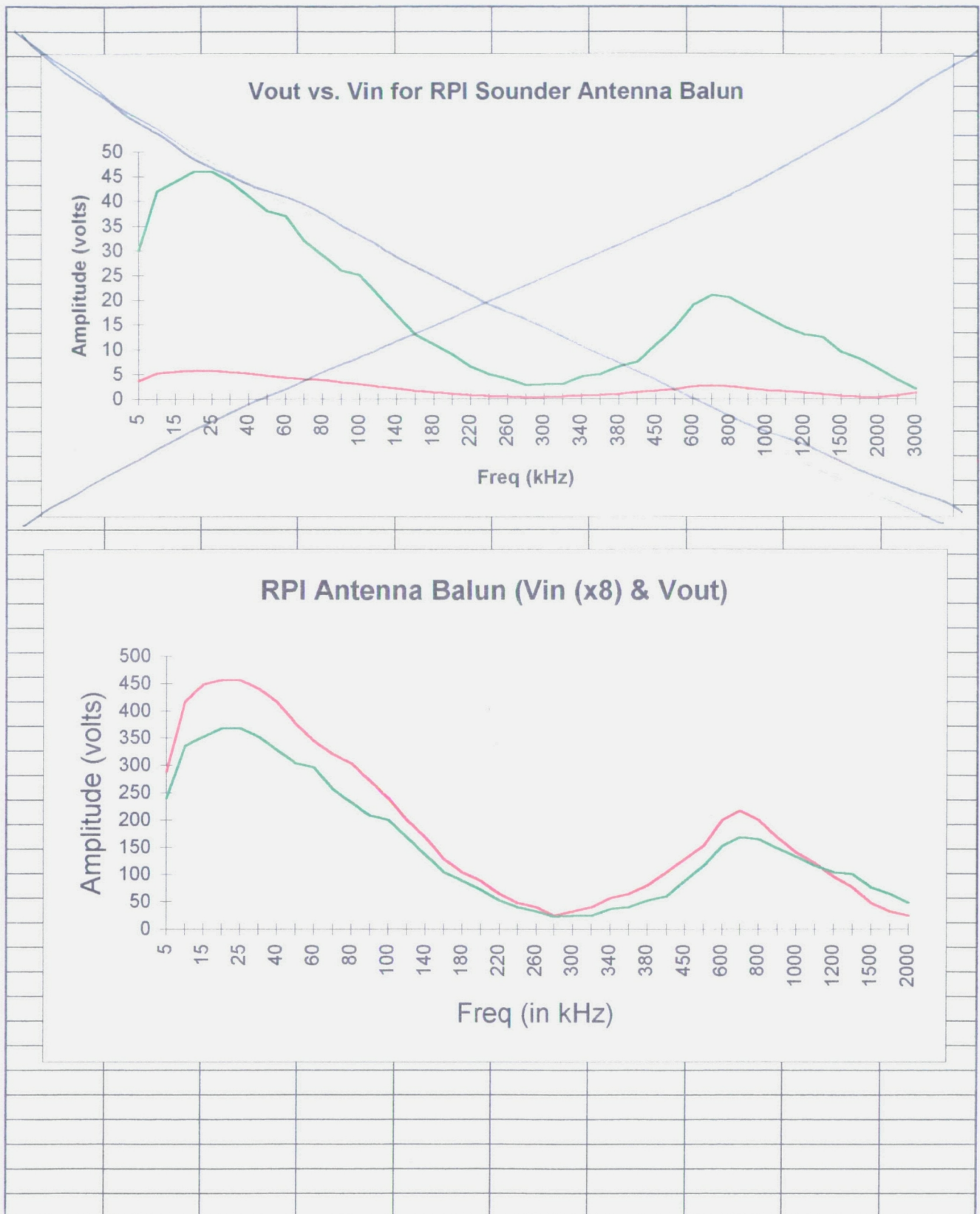


Figure 5.5 Antenna Balun Performance

500m Dipole Impedance & Radiated Power

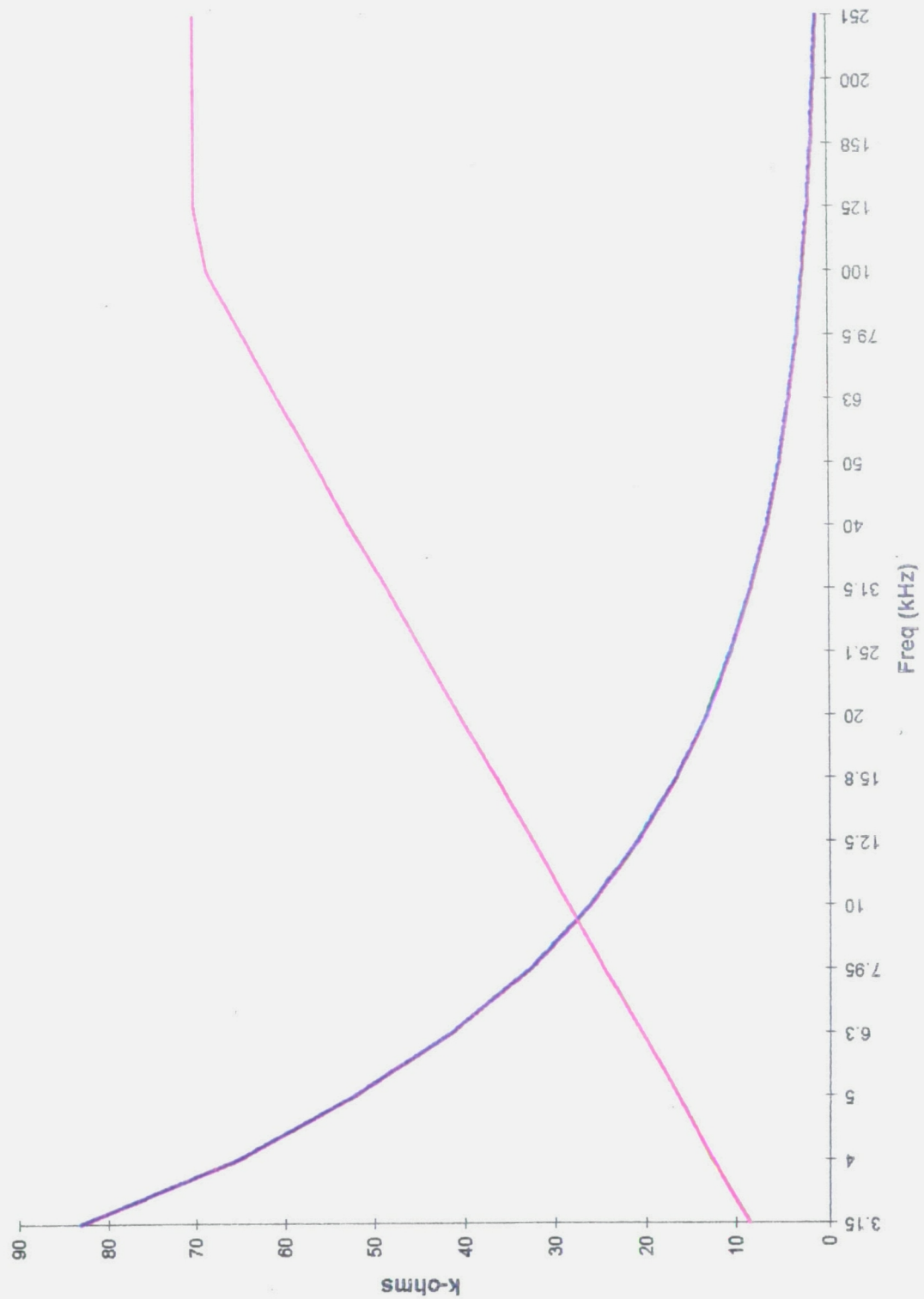


Figure 5.6 500m Dipole Impedance and Radiation Efficiency

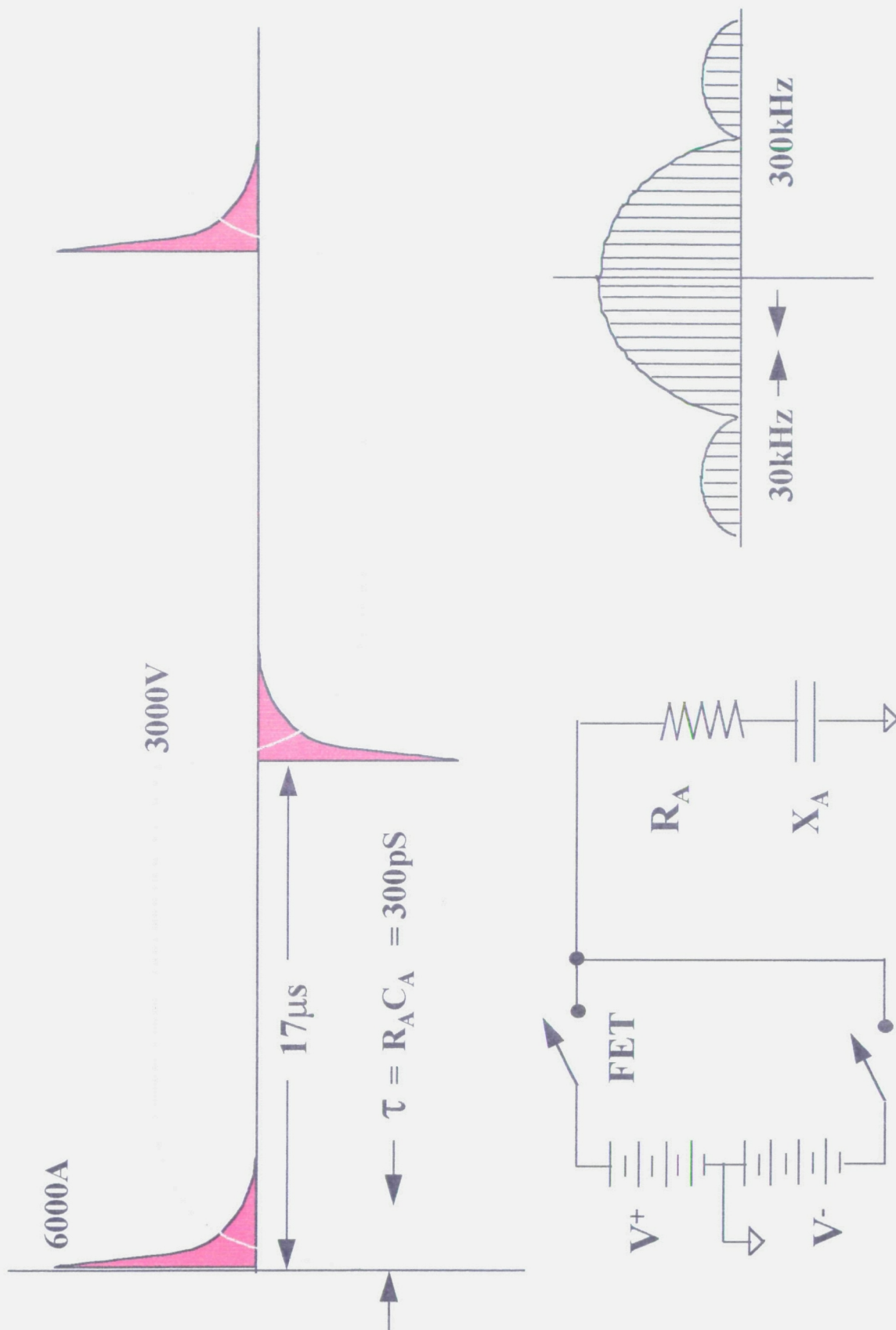


Figure 5.7 High Voltage Amplifier into 500m Dipole

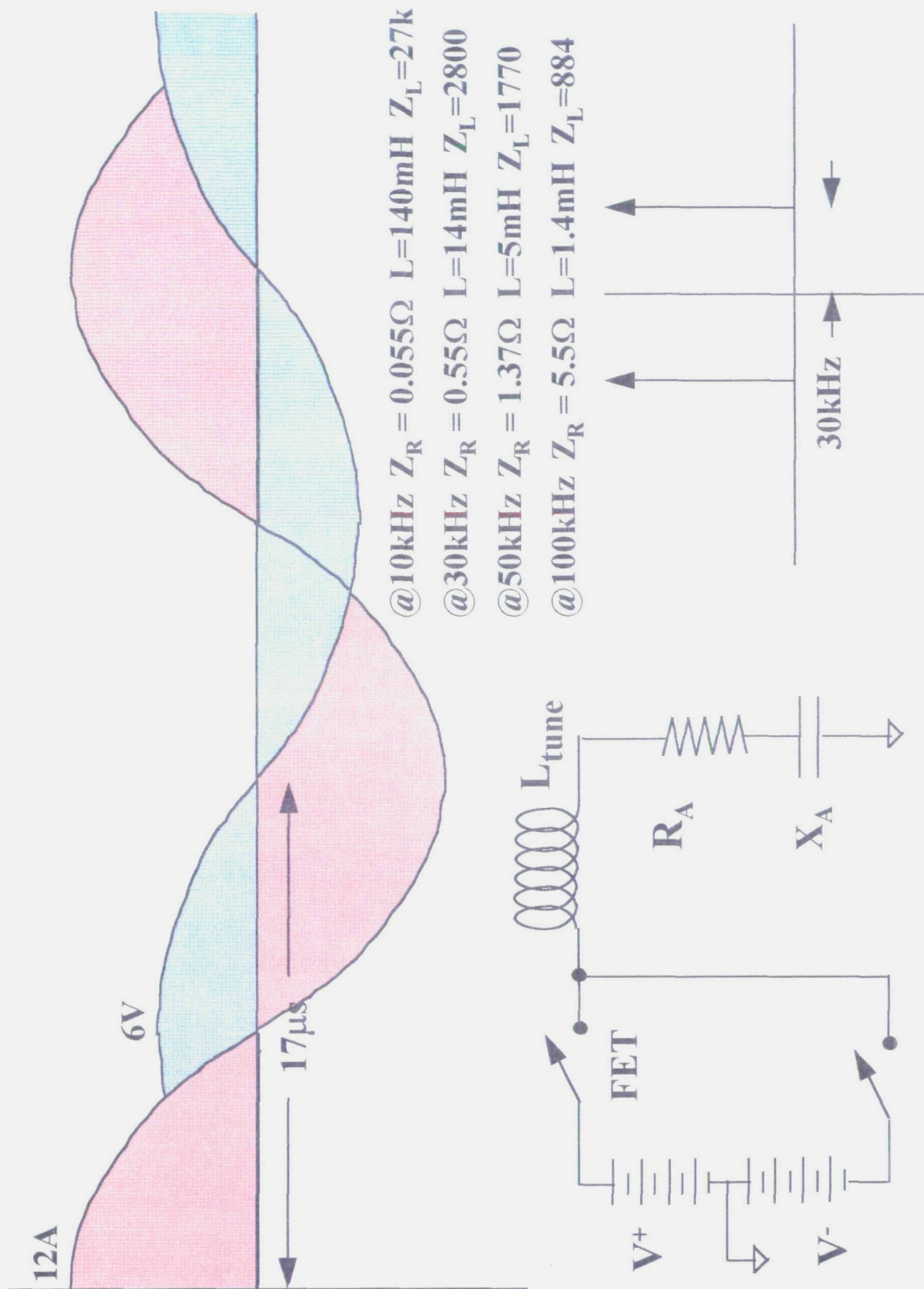


Figure 5.8 Tuned Amplifier into 500m Dipole

An additional advantage to a tuning circuit at the base of the antenna is that the tuning inductance can be realized with a magnetically coupled transformer, as shown in Figure 5.9. This device provides isolation of the internal electronic circuitry from the space environment, thus reducing susceptibility to high voltage space charging effects. In reality, for the 600pF capacitance of the 500m dipole antenna, the tuning inductor implied by Figure 5.8 would have to be on the order of 0.5H, and a smaller spin axis antenna would require a tuning inductor of several Henries. Since large value low-loss inductors are difficult to produce, a parallel capacitance can be added across the antenna and across the amplifier output, making a classic "PI" matching network. This brings the inductor value down to about 25mH for the 500m antenna and .25H for the 10m antenna. The 10m antenna is necessary for angle of arrival measurements during signal reception, but need not be used to transmit, therefore, its large tuning inductor can be made physically small since very little power needs to be passed through it.

Design of an Antenna Matching Network

Two antenna matching networks, a PI type and an L type, were analyzed for the 10m antenna to match a receiver input impedance of approximately 5000ohms to an antenna impedance as high as 800,000 ohms. The designs were tested using the Numeric Electromagnetics Code (NEC), a computer simulation program for Electromagnetic Structures. Standard calculations for a PI network and L network were used to convert the optimized design for use with the 500m dipole and tests of the dipole impedance match were made.

We will look at the PI matching network first. The circuit shown in Figure 5.10 models the PI matching network using NEC for component values which set the operating frequency at about 14kHz. The model is illuminated by a 1V/m electric field, and the values shown in Figure 5.11 are the resulting voltages at the input to the receiver. The top four graph lines pertain to variations of the PI network model, while the bottom two traces are L network results. The first line (the top label in the legend box) uses a .56H inductor with C1=240pF and C2=1.47nF with a 5000 ohm load. The second line changes to a .21H inductor, C1=530pF and C2=4.6nF with a 5000 ohm load, then the third line changes the load to 2500ohms. The fourth line is the same as the second, except a 16m rather than 10m antenna is used.

Still looking at Figure 5.11, the two L-network models (the generic PI and L models are shown in Figure 5.10) also use a .56H inductor, with Cp=Cs=100pF, then with Cp=50pF and Cs=150pF. The amplitude of the 1V/m signal vs frequency indicates antenna efficiency, impedance matching, and bandwidth (or $Q = f/\Delta f$) of the matching circuit. For reception the purpose of the matching network is to allow use of a lower receiver input impedance (R_{in}), since the electronic (i.e. thermal) noise at the first receiver amplifier is determined by the temperature and impedance by the factor,

$$\text{Noise Voltage} = (R_{in} * NF * kT\Delta f)^{1/2}$$

where NF is the Receiver Noise Figure (about 3), k is Boltzmann's constant, T is temperature in (°K), and Δf is the circuit bandwidth in Hz. To the extent that the matching network steps down the impedance faster than it steps down the signal power, a gain in receiver sensitivity is achieved; the optimum power transfer occurs when the impedance at the input to the network is equal to the antenna impedance.

High Voltage Isolation by Tuning & Magnetic Coupling

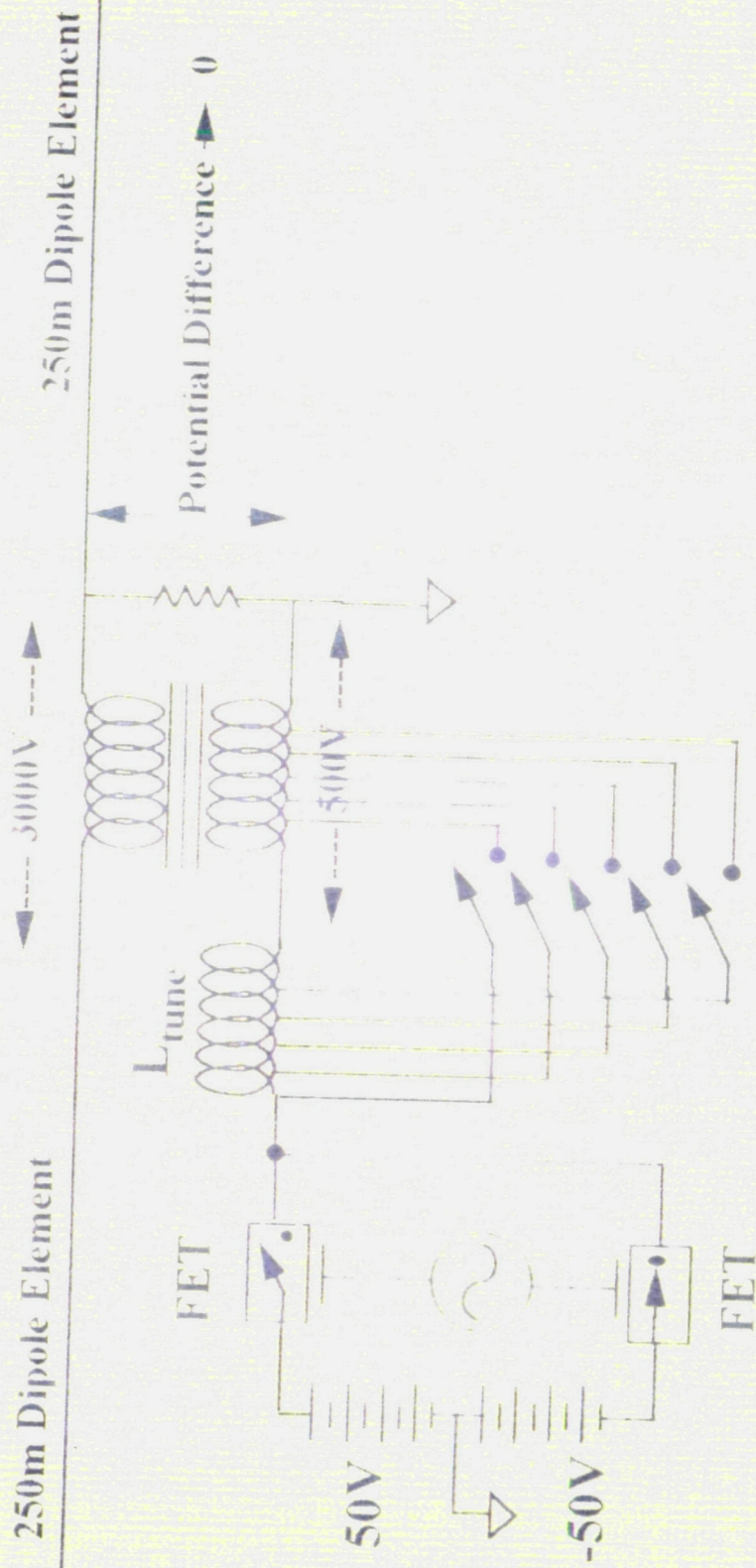
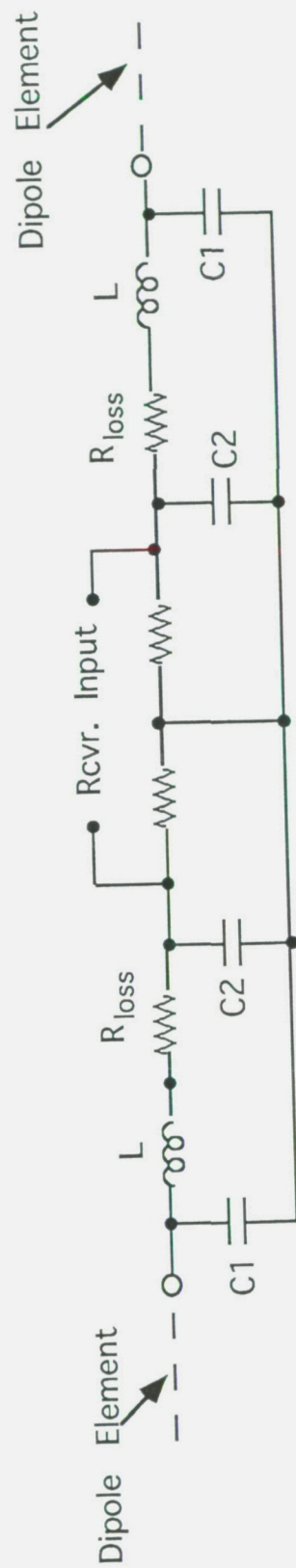


Figure 5.9 Tuned Magnetic Coupling of 500m Dipole Antenna

PI Matching Network



L Matching Network

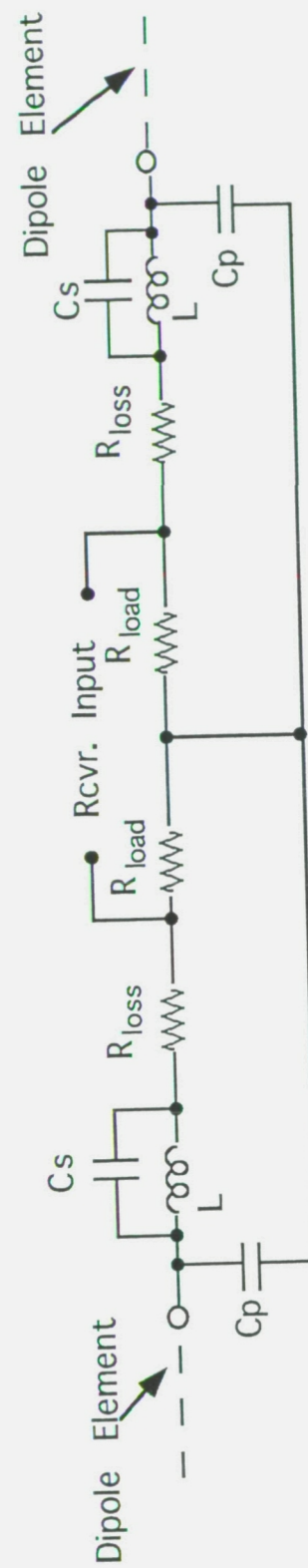


Figure 5.10 PI and L Matching Networks

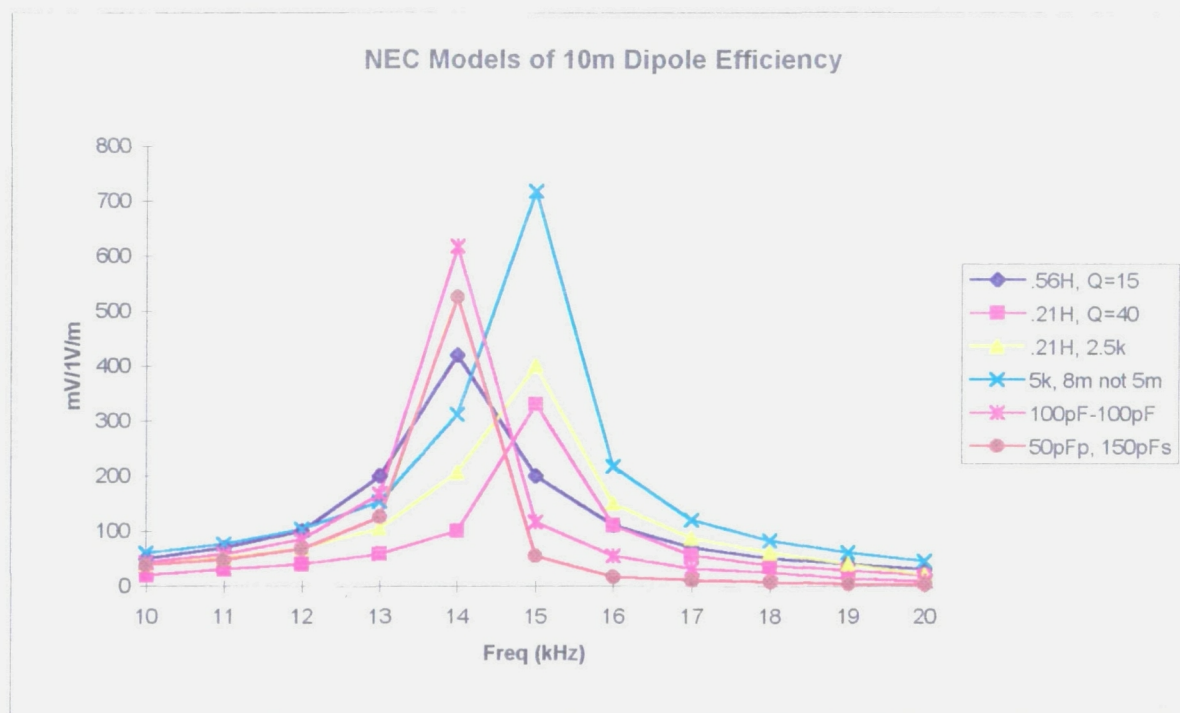
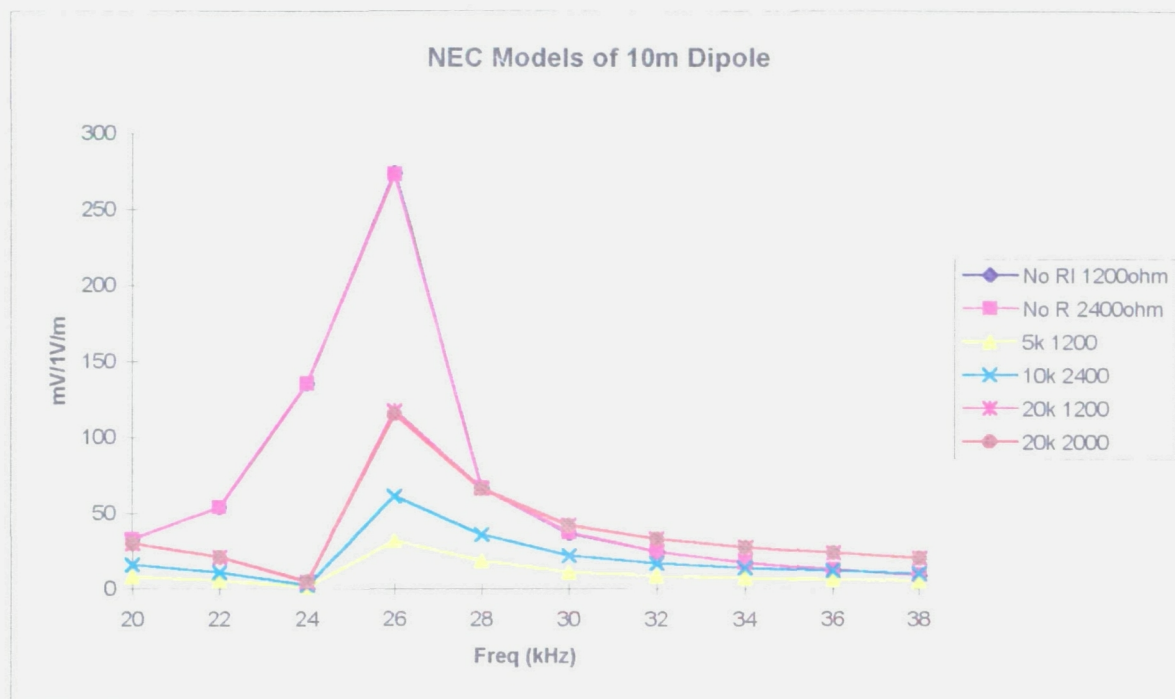


Figure 5.11 Transfer Characteristics of PI and L Networks (NEC model)

5.5 Potential electromagnetic Interference to the RPS

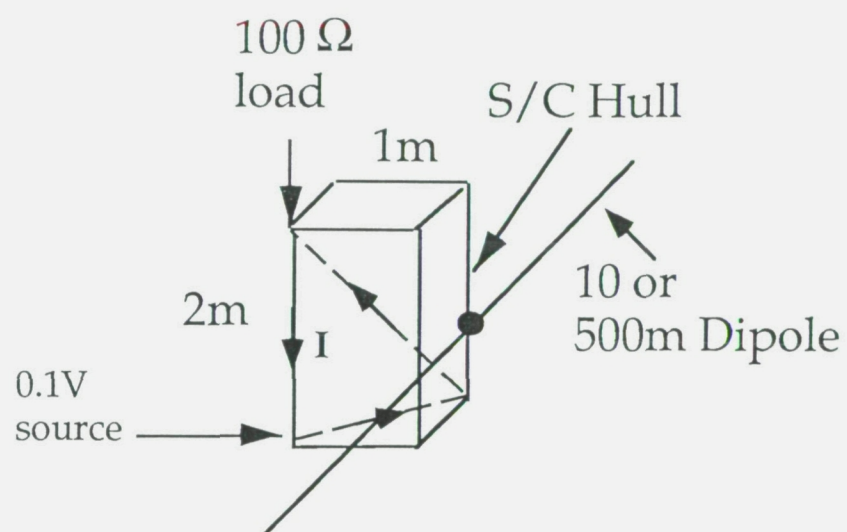
A simple model was developed and analyzed using the Numerical Electromagnetics Code (NEC) to determine the level of interference that may be received by the RPS from other systems on-board a satellite platform. Since an actual platform has not been identified, the model was intended to be a worst case, such that the problem of electromagnetic coupling to other systems could be bounded. The results are very encouraging due to the inefficient radiation at these frequencies by any structures with dimensions less than a satellite diameter. The Marshall Space Flight Center specification for EMC requirements, MSFC-SPEC-521B, was used to establish criteria for acceptable performance.

The model used is a single wire right-angled triangular loop with a height of 2m and hypotenuse of 2.83m with the 500m RPS dipole antenna oriented at a 45° angle to the plane of the loop, as shown in Figure 5.12. No shielding is considered, neither from cable shielding nor from the skin of the satellite, so this first configuration is "way beyond a worst case". The model applies a 0.1V source at 30kHz (as might result from ripple on a power line) with a 100ohm load distributed in the loop to generate a 1mA current. The level of the interfering signal picked up at the feed point of the large dipole antenna is then computed. The 0.1V applied across the loop could also be caused by an electric field intensity of roughly 100mV/m, which is 60dB above the E-field limit in the MSFC specifications. This test resulted in 0.6 μ V at the input to the RPS receiver corresponding to a maximum input voltage of 0.6 nV for an E-field compliant with MSFC specifications. This is 34 dB below the thermal noise input voltage of approximately 30nV for a 300Hz bandwidth receiver, i. e. negligibly small.

5.6 Electromagnetic Interference to Collocated Satellite Systems Caused by RPS

The model used on the previous section was applied to analyze interference caused by the RPS which could eventually affect other on-board systems. By driving the 500m dipole with 1 Watt of RF power, the current induced in the triangular loop can be analyzed. With a 100ohm load, the current was 4.4mA, or 0.44V across the resistor. This is quite high but the MSFC spec states that "Emissions on Authorized Transmitter Frequencies are excluded from this requirement". Even so, this analysis contained no shielding whatsoever, therefore the results can be used as a starting point to determine how much shielding is needed for any given system to avoid degradation by the RPI transmitted signal.

The above two sections show that the RPS should have no problems coexisting with other instruments on board.



5.12 Model Used for Electromagnetic Compatibility/Susceptibility

6.0 CONCLUSION

In the Marshall Space Flight Center NRA8-8 (Techniques and Technologies for Magnetospheric Imaging), five Technical Areas have been identified. This work supports Technical Area 5 (*i.e.*, other Unique Imaging Techniques). In particular, it investigates the concept of magnetospheric radio sounding to make remote density measurements of unprecedented precision and coverage in the plasmasphere, inner magnetosphere and magnetopause. These measurements would produce images of magnetospheric electron density structures and would be complementary to the techniques identified in the other four Technical Areas of NRA8-8. They would provide unique remote electron density information for enhancing the physical interpretation of other remote measurements from such spacecraft as the proposed Inner Magnetospheric Imager (IMI).

6.1 Capabilities Verified by the Present Work

The challenge of radiating sufficient power on the electrically short dipole antenna seems to be achievable. With a tuning network of modest Q value (e.g. 15) the loss of 20 to 30dB between the amplifier and the antenna must be accepted at the low frequencies. This is within the expected range as shown in Figure 5.5 where less than 10mW is actually radiated when using a 10W transmitter.

6.2 Recommendations for Future Work

Future work directed toward the goal of successful imaging of magnetospheric electron density structures would include a thorough investigation of advanced data processing techniques, advanced methods for signal processing, and 3-dimensional ray tracing using the latest magnetospheric models. The first step in studying advanced signal processing is pursued by Taylor et al. [1995], and 3-dimensional ray tracing using the latest magnetospheric models is carried out by the RPI team [Fung et al., 1995].

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